

HIGHLY CONFIGURABLE PLL ARCHITECTURE  
FOR PROGRAMMABLE LOGIC

Background of the Invention

This invention relates to programmable logic integrated circuit devices, and more particularly to configurable phase-locked loop (PLL) circuitry for programmable logic devices.

Programmable logic integrated circuit devices are well known and often include large numbers of programmable logic blocks, memory blocks, and programmable interconnection resources. Logic blocks are programmable by a user to perform various logic functions desired by the user. Memory blocks may be used by the user to store and subsequently output data. Interconnection resources are programmable by the user to make any of a wide range of connections between inputs of the programmable logic device and inputs of the logic and memory blocks, between outputs of the logic and memory blocks and outputs of the device, and between outputs and inputs of the logic and memory blocks. Although each logic block is typically able to perform only a relatively small logic task, such interconnections allow the programmable logic device to perform extremely complex logic functions.

Providing PLL circuitry on programmable logic devices is also well known. PLL circuitry produces an output signal that is continually adjusted to maintain a constant frequency and phase relationship with an input reference signal (the PLL circuitry thus "locks" onto that frequency and phase relationship). PLL circuitry may be used to counteract clock signal propagation delay on the programmable logic device, convert from one clock signal frequency (e.g., an input clock signal frequency) to another different clock signal frequency (e.g., to be output by the device), and more generally to provide one or more external clock signals, internal global clock signals, or internal local/regional clock signals.

The configurability of known PLL circuitry, however, is typically limited. For example, the frequency range of output signals produced by known PLL circuitry may be too narrow for many applications in which a programmable logic device could be used. Furthermore, the number and configurability of PLL outputs may be too limited. For example, known PLL circuitry may not have enough outputs available for connection to I/O pins for off-chip clocking applications. Moreover, known PLL circuitry may not have enough outputs available for connection to on-chip global or local clocking networks. Thus, the configurability of known PLL circuitry on programmable logic devices may limit the number of designs that can be implemented on the device and thus the number of applications in which a programmable logic device could otherwise be used.

In view of the foregoing, it would be desirable to be able to provide highly configurable PLL circuitry in order to increase the number of designs and applications in which programmable logic devices can be used.

Summary of the Invention

In accordance with the invention, programmable logic devices are provided with highly configurable phase-locked loop (PLL) circuitry. PLL circuitry of the invention outputs multiple signals of which each can be programmably connected to any or all of the following: one or more I/O pins for use as an external (e.g., off-chip) clock, one or more internal (e.g., on-chip) global clock networks, one or more internal local/regional clock networks, and combinations thereof. The PLL circuitry performs phase-shifting with respect to an input reference signal such that each output signal can have a different phase if desired. Furthermore, the frequency of each output signal can be individually programmed. In other embodiments of the invention, PLL outputs can be programmably cascaded in selectable numbers of stages to provide output signal frequency ranges that are orders of magnitude wide. In still other embodiments of the invention, PLL circuitry can receive multiple input signals (e.g., from off-chip and/or on-chip sources) from which a reference signal can be programmably selected.

Methods of providing such clock signal outputs are also provided in accordance with the invention.

Advantageously, PLL circuitry and methods of the invention can be used to implement a wide range of designs including, for example, frequency synthesizers and zero delay buffers. This notably increases the number of designs and applications in which a programmable logic device can be used.

Brief Description of the Drawings

The above and other advantages of the invention will be apparent upon consideration of the following detailed 5 description, taken in conjunction with the accompanying drawings, in which like reference characters refer to like parts throughout, and in which:

FIG. 1 is a simplified block diagram of an 10 illustrative embodiment of representative portions of a programmable logic integrated circuit device according to the invention;

FIG. 2 is a simplified block diagram of a first embodiment of PLL circuitry according to the invention;

15 FIG. 2a is a simplified block diagram of an embodiment of a dynamically configurable multiplexer according to the invention;

FIG. 3 is a more detailed, but still simplified block diagram of a typical portion of the PLL circuitry of FIG. 2;

20 FIG. 4 is a simplified block diagram of another embodiment of PLL circuitry according to the invention;

FIGS. 5, 5a, and 5b are simplified block diagrams illustrating programmable logic integrated circuit devices employing PLLs configured in transmit and receive modes 25 according to the invention;

FIG. 6 is a simplified block diagram of a synchronizing circuit for PLL circuitry according to the invention;

FIG. 6a is a timing diagram of signals from FIG. 6;

30 FIG. 6b is a simplified block diagram of an alternative portion of the synchronizing circuit of FIG. 6 according to the invention;

FIG. 7 is a simplified block diagram of a clock multiplexing pattern according to the invention;

FIG. 8 is a simplified block diagram of an external clock multiplexing pattern according to the invention;

5 FIG. 9 is a simplified block diagram of a cascaded portion of PLL circuitry according to the invention;

FIG. 10 is a simplified block diagram of configurable clock buffer circuitry according to the invention;

10 FIG. 11 is a simplified block diagram of PLL enablement circuitry according to the invention; and

FIG. 12 is a simplified block diagram of an illustrative system employing the invention.

15 Detailed Description of the Invention

FIG. 1 shows an illustrative programmable logic integrated circuit device (PLD) 100 in accordance with the invention. PLD 100 has one or more clock signal input pins 102 for receiving one or more clock signals from circuitry external to the device. PLD 100 also includes a plurality of input/output ("I/O") pins 104 for receiving data and/or control signals from external circuitry. (For convenience herein, all data and control signals other than clock signals will be referred to simply as data signals.)

20 25 The data signals from pins 104 may be applied to I/O registers 106 for temporary storage and output by those registers. An input clock signal applied to a pin 102 may be applied to I/O registers 106 to control the operation (in particular, the timing) of those registers. The data signals 30 output by registers 106 are applied to programmable logic 108 of PLD 100. (As an alternative to using registers 106, data from pins 104 may be applied more directly to logic 108

(i.e., without first being input to registers 106).)

Programmable logic 108 may also receive an input clock signal from a pin 102 and generally performs at least some operations on the input data from pins 104 and/or

5 registers 106 at a rate determined by the frequency of a received clock signal. In other words, some or all of the data applied to pins 104 may be synchronized with a clock signal received from a pin 102, and programmable logic 108 may partially process that data in synchronism with that  
10 clock signal.

Multiple input clock signals applied to pins 102 may be applied to phase-locked loop ("PLL") circuitry 110 in accordance with the invention. PLL circuitry 110 may also receive an internal clock signal from programmable logic 108,

15 which may have been generated on PLD 100 and/or derived from another clock signal received from one of clock pins 102.

PLL circuitry 110 programmably selects one of the input clock signals for use as an input reference signal and provides multiple modified clock output signals which have desired  
20 frequency relationships to the input reference signal. For example, the frequencies of the modified clock output signals produced by PLL circuitry 110 may be higher and/or lower than the input reference signal frequency. The modified clock signals produced by PLL circuitry 110 advantageously may be  
25 programmably applied to any or all of clock signal output pins 112, programmable logic 108, and I/O registers 114.

Programmable logic 108 can be configured to perform at least some data processing at one or more rates determined by the one or more modified clock signals produced by PLL  
30 circuitry 110. For example, programmable logic 108 may perform some data processing in synchronism with a modified clock signal produced by PLL circuitry 110. Output data

signals from programmable logic 108 may be applied to I/O pins 116, possibly via I/O registers 114, which may register those data signals on their way to pins 116 at possibly another modified clock signal rate. Furthermore, PLD 100 may 5 output data via pins 116 at a modified clock signal frequency that may or may not be the same as, and/or in synchronism with, any of the modified clock signals applied to output clock pins 112.

10 Note that in other embodiments of the invention (see, e.g., FIG. 10 and its accompanying description below), pins 102 and 112 may be dynamically used as either clock or data I/O pins.

15 Although FIG. 1 may appear to show fixed interconnections among the various circuit elements, note that on a programmable logic device such as PLD 100 there is typically a high degree of programmability and therefore signal routing flexibility in the interconnection resources that are provided. This programmability of interconnection resources, which is well known in the art, is not shown to 20 avoid unnecessarily complicating the FIGS. Thus not all of the interconnections shown in FIG. 1 (or in any of the subsequently described FIGS.) may be present in all uses of PLD 100, and/or other interconnections not shown in FIG. 1 (or other FIGS.) may be present in some uses of PLD 100.

25 Those skilled in the art will also appreciate that the circuit elements and interconnection resources shown in FIG. 1 may be only a part of more extensive circuit element and interconnection resources provided on PLD 100. Examples of programmable logic devices in which the invention can be 30 implemented are found in Cliff et al. U.S. Patent No. 5,689,195; Cliff et al. U.S. Patent No. 5,909,126; and

Jefferson et al. U.S. Patent No. 6,215,326; all of which are hereby incorporated by reference herein in their entireties.

FIG. 2 shows an embodiment of PLL circuitry in accordance with the invention. PLL circuitry 210 receives an input reference signal via input 218 (unlike PLL circuitry 110, only one input signal is received in this embodiment). That input signal is applied to prescale frequency divider 220. Divider 220 divides the frequency of the input reference signal by a factor N, which is preferably a programmable parameter of PLD 100 stored in, for example, a programmable function control element of PLD 100. The output of divider 220 is applied as a driving clock signal to one input of phase/frequency detector (PFD) circuitry 222. PFD circuitry 222, which can be conventional, also receives the output signal of feedback frequency divider 224. PFD circuitry 222 produces an output signal which is indicative of the phase/frequency difference between the two signals applied to it. (A more complete depiction of PFD circuitry 222 is shown in FIG. 3 and described below). The output signal of PFD circuitry 222 is applied as a control signal to voltage controlled oscillator (VCO) 226. VCO 226 produces  $k_1$  output signals (where  $K_1$  is an integer), each of which is phase-shifted by preferably an increasing multiple of  $360^\circ/k_1$ . In one embodiment, for example, VCO 226 may output six signals (i.e.,  $k_1 = 6$ ), wherein the output signals are each preferably phase-shifted with respect to the input reference signal at  $60^\circ$  intervals (e.g.,  $60^\circ$ ,  $120^\circ$ ,  $180^\circ$ ,  $240^\circ$ ,  $300^\circ$ , and  $360^\circ$ ). In another embodiment, for example, eight signals may be output (resulting in  $45^\circ$  phase shift increments). The output signals of VCO 226 are applied to multiplexer circuitry 228 and feedback multiplexer 230.

Multiplexer 230 feeds one of the VCO 226 output signals to feedback frequency divider 224. The particular VCO 226 output signal fed to divider 224 can be fixed by design, programmed by a user, or rotated or alternated among 5 the VCO 226 output signals by control logic that either is fixed by design or programmed by a user. Divider 224 divides the frequency of the signal applied to it by factor M to produce the above-mentioned second (feedback) input to PFD circuitry 222. Factor M is preferably a programmable 10 parameter of PLD 100 stored in, for example, a programmable function control element of PLD 100.

Multiplexer circuitry 228 receives all  $k_1$  VCO 226 output signals and programmably selects which of those signals to feed to post-scale frequency-divider 15 circuitry 232. Divider circuitry 232 preferably includes multiple counter/frequency-divider circuits, which in the embodiment shown in FIG. 2 is six. Note that the number of individual counter or frequency-divider circuits does not have to equal the number of VCO output signals. Multiplexer 20 circuitry 228 is preferably programmable by a user, but may alternatively be fixed to output, for example, each VCO output signal to a respective one of the individual frequency-divider circuits, assuming the number of divider circuits equals the number of VCO output signals. Each 25 individual divider circuit divides the frequency of the signal applied to it by its corresponding factor  $C_0 - C_{n_1}$  (where  $n_1$  is an integer and in FIG. 2 equals five). Each of factors  $C_0 - C_{n_1}$  is preferably an independently programmable parameter stored in, for example, one or more programmable 30 function control elements of PLD 100. Thus, each of factors  $C_0 - C_{n_1}$  may be different, the same, or combinations thereof.

The resulting output signals of post-scale frequency-divider circuitry 232 are applied to multiplexers 234, 236, and 238. Multiplexers 234, 236, and 238 are each dynamically programmably controlled to 5 output any one of their inputs to any one of their outputs. Multiplexer 234 couples selected signals to up to  $k_2$  clock I/O pins (CLKOUT; e.g., pins 112 of FIG. 1). Constant  $k_2$  is an integer typically less than or equal to  $k_1$ . For example, if  $k_1$  is equal to eight,  $k_2$  may be equal to six. 10 Multiplexer 236 couples selected signals to up to  $k_3$  global clock (GCLK) networks. Constant  $k_3$  is also an integer typically less than or equal to  $k_1$ . Thus, for example, if  $k_1$  is equal to eight,  $k_3$  may be equal to four. Lastly, 15 multiplexer 238 couples selected signals to up to  $k_4$  local clock (LCLK) networks. Constant  $k_4$  is likewise an integer typically less than or equal to  $k_1$ . For example, if  $k_1$  is equal to eight,  $k_4$  may also be equal to eight. Moreover, the eight may be two groups of the same four signals for use in two local regions designed to have the same clocking.

20 FIG. 2a shows an embodiment of a dynamically configurable multiplexer that can be used for each of multiplexers 234, 236, and 238 in accordance with the invention. Multiplexer 235 includes a group 237 of inputs which are dynamically selectable by a user. Advantageously, 25 multiplexer 235 allows any one of a PLL output, clock pin, or core signal, for example, to be selectively driven onto, for example, a global (gclk) or local (lclk) clock network. Signals CR\_GCLKMUXCTRL and CR\_GCLKMUXSEL are programming bits used to either configure multiplexer 235 to be dynamically 30 reconfigurable or fixed (i.e., not dynamically reconfigurable). An embodiment of enablement circuitry 239 is shown in FIG. 11 and described further below.

Advantageously, PLL circuitry 210 provides a high degree of configurability. For example, by appropriately programming multiplexer circuitry 228 and divider circuitry 232, the six modified clock signals produced by 5 circuitry 232 can have different phases and different frequencies, different phases and the same frequencies, the same phase and different frequencies, or combinations thereof. Moreover, each of the six modified clock signals can be programmably routed where needed. None are limited or 10 partitioned to only particular circuits, I/O pins, or uses.

FIG. 3 shows an embodiment of phase/frequency detector (PFD) circuitry 222. PFD circuitry 322 typically includes a phase/frequency detector circuit 323, which receives the input and feedback clock signals. Detector 15 circuit 323 produces "up" or "down" output signal pulses depending on whether the phase of the input clock signal leads or lags the phase of the feedback clock signal. The width of the "up" or "down" signal pulses is typically controlled by detector circuit 323 to be proportional to the 20 phase difference between the input and feedback clock signals. The "up" or "down" signals are fed to charge pump circuit 325, which provides a transfer function of those signals to an output signal voltage at a level between the power supply voltage of PLD 100 and ground. The "up" and 25 "down" signals switch an internal current source to deliver a charge to move the charge pump output signal voltage up or down during each clock cycle. The output signal of charge pump circuit 325 is applied to low-pass filter circuit 327, which smoothes the signal for application as a control signal 30 to an associated VCO (e.g., VCO 226). In sum, when the phase of the input clock signal leads the phase of the feedback clock signal, an "up" signal is generated by detector

circuit 323. This results in an increase in the frequency of the feedback clock signal. Conversely, when the phase of the input clock signal lags the phase of the feedback clock signal, detector circuit 323 produces a "down" signal, which 5 causes a decrease in the frequency of the feedback clock signal.

FIG. 4 shows another embodiment of PLL circuitry in accordance with the invention. PLL circuitry 410 includes prescale frequency divider 420, phase/frequency detector 10 (PFD) circuitry 422, voltage controlled oscillator (VCO) 426, multiplexer circuitry 428, feedback multiplexer 430, post-scale frequency-divider circuitry 432, and multiplexers 434, 436, and 438. These elements operate similarly, if not identically, to the corresponding elements 15 of PLL circuitry 210. Note that the number of outputs shown in FIG. 4 for VCO 426 (8 outputs), multiplexer circuitry 428 (6 outputs), multiplexer 434 (6 outputs), multiplexer 436 (4 outputs), and multiplexer 438 (8 outputs) are merely 20 illustrative and that these elements may be configured or replaced with other elements to have more or less outputs.

PLL circuitry 410 advantageously has enhanced input signal selection and synchronization capability. PLL circuitry 410 includes multiplexers 440, 442, and 448, synchronizing circuit 446, switchover circuit 450, and AND 25 gate 452. Multiplexers 440 and 442 both receive multiple input signals from a number of clock input pins (which in this embodiment is four; note that other numbers of input signals from clock pins may be used). These clock input pins are preferably closely located and available as a matched 30 reference to PLL circuitry 410. Any of these pins may be used for I/O delay compensation and clock network delay compensation. These pins may be used, for example, by memory

interfaces, such as for RLDRAM (reduced latency dynamic random access memory).

Multiplexers 440 and 442 both also receive a core input clock signal, which may be an internal clock signal 5 originating from any clock pin on the chip or it may be generated by another PLL on the chip. Advantageously, this input, if selected, allows the PLL reference clock signal to come from another PLL on the chip via, e.g., PLL cascading. A single reference clock can therefore be used to drive 10 multiple PLLs, rather than having separate clocks (typically requiring respectively separate I/O clock pins) drive respective PLLs. This feature is particularly useful for multiple PCI interfaces, multiple memory interfaces, and those interfaces adhering to known source synchronous 15 protocols where multiple transmit channels using a common reference clock are required.

FIG. 5 shows an embodiment of a PLD in accordance with the invention in which a core clock signal is used to drive multiple PLL circuitries adhering to a source 20 synchronous protocol. PLD 500 includes core clock network 554 and PLL circuitries 510a-h, which are each preferably LVDS PLL circuitries. LVDS (low voltage differential signaling) is a signaling protocol employing very low voltages and differential signaling, which involves 25 the transmission of pairs of signals that propagate in parallel. Each signal is usually a logical complement of the other. That is, when one signal is at a high voltage (e.g., a logical 1), the other is at a low voltage (e.g., a logical 0), and vice versa. LVDS PLL circuitries 510a-d 30 operate in transmit mode (TX), while LVDS PLL circuitries 510e-h operate in receive mode (RX). (Note that PLL circuitries 510a-h can each operate in either or both

modes in accordance with the invention). RX PLL circuitries 510e-h receive external clock signals from clock pins 502 and generate modified clock signals that can be used on-chip, off-chip, or both. TX PLL circuitries 510a-d each 5 receive a core clock signal that can enter clock network 554 at node 556. This core clock signal may be driven by any clock pin or by any general purpose or LVDS PLL circuitry output. This core clock signal can advantageously serve as the input reference signal to LVDS PLL circuitries 510a-d, 10 which then generate modified clock signals that can be used on-chip, off-chip or both.

FIG. 5a further illustrates PLL circuitry operating in receive mode. PLL circuitry 510j receives an external clock from clock pins 502. This external clock has its edge 15 in a particular phase relationship with data being received at I/O pins 504. PLL circuitry 510j generates several clocks. One is a high speed clock at output 558 used for registers 506, which are closest to the I/O pins. A second clock at output 560 is at a lower speed. It is equal to the 20 high speed clock frequency divided by a deserialization factor. A common deserialization factor is 8, resulting in a clock frequency 1/8 the frequency of the clock at output 558. This second clock is routed to a second set of registers. A third clock at output 562 typically has the same frequency as 25 the second clock and is routed to registers in programmable logic 508. Multiple registers are used for each data channel, and the number of registers preferably equals the deserialization factor. PLL circuitry 510j advantageously establishes and maintains the phase relationship and 30 frequency of clocks at outputs 558, 560, and 562 with respect to the external clock. Note that in receive mode, PLL circuitry 510j uses only the reference clock sent with the

data. Thus, individual PLL circuitry is used for each interface, because each interface can have a different phase of frequency relationship.

FIG. 5b further illustrates PLL circuitry operating in transmit mode. In transmit mode, the source synchronous channel sends out both data (at I/O pins 516) and a TX clock (at clock pins 512). PLL circuitry 510k can therefore receive a reference clock from any pin or internally generated core clock because no phase relationship is required between this reference clock and the TX data and clock. If multiple channels are required, a single core clock advantageously can be used to drive multiple TX PLL circuitries, as shown in FIG. 5.

Returning to FIG. 4, multiplexers 440 and 442 are programmable preferably by a user to select two of the multiple input signals to feed to synchronizing circuit 446. Synchronizing circuit 446 ensures that the start-up of PLL circuitry 410 occurs in a synchronous manner. In particular, circuit 446 is intended to prevent glitches on the reference clock signal, which could result in erroneous timing for PLL circuitry 410.

FIG. 6 shows an embodiment of a synchronizing circuit in accordance with the invention. Synchronizing circuit 646 includes latches 647 and 649 and AND gates 651 and 653. Latch 647 receives at input 655 the input signal selected by multiplexer 440, while latch 649 receives at input 657 the input signal selected by multiplexer 442. A PLL start signal enables the reference clock on the falling edge to ensure that adequate time is allowed before the next rising edge of the clock. Corresponding waveforms are shown in FIG. 6a.

Additional registers could be inserted to delay the enabling of the reference clock to allow portions of the PLL circuitry to be enabled before the two output signals, CLKIN0 and CLKIN1, begin toggling. This alternative embodiment is 5 illustrated in FIG. 6b, where the PLL start signal is used to generate a staged start-up sequence that first enables the counters/frequency dividers and then the VCO.

Returning to FIG. 4, the two synchronizing circuit outputs are fed to multiplexer 448 and switchover 10 circuit 450. Multiplexer 448 is programmable by a user and accordingly outputs one of the two signals selected by the user to serve as the input reference signal. The selected input reference signal is fed to AND gate 452, which also receives an input signal from switchover circuit 450. In 15 normal operating mode, switchover circuit 450 allows the selected reference signal to propagate through AND gate 452 to prescale frequency divider 420. Switchover circuit 450 monitors the two output signals received from synchronizing circuit 446. If the selected clock signal stops running for 20 some reason, switchover circuit 450 will automatically cause the other output signal from synchronizing circuit 446 to be used as the input reference signal. This feature can be used for clock redundancy or for a dual clock domain application. Moreover, switchover circuit 450 can be preferably manually 25 controlled based on a user control signal. This allows a user, for example, to switch between two input reference signals of different frequencies.

PLL circuitry 410 further has enhanced feedback capability and includes feedback frequency divider 424, 30 spread spectrum counter 458, and multiplexer 460. Multiplexer 460 is programmable and receives an output signal from multiplexer 430 and an external feedback signal. By

programming multiplexer 460 to output the external feedback signal, an external clock signal can be aligned with the input reference clock signal. This advantageously allows a user to remove clock delay and skew between devices/chips.

5 Spread spectrum counter 458 helps prevent corrupted data and intermittent system errors that can be caused by radiated noise from high frequency clock signals. Spread spectrum counter 458, which is coupled to frequency dividers 420 and 424, accomplishes this by modulating clock frequencies  
10 over a small range.

PLL circuitries 210 and 410 are both advantageously fully programmable both at power up and during user mode (i.e., dynamically), thus providing a high degree of flexibility. Programmable parameters include coarse and fine  
15 phase shifting, counter values (i.e., frequency divisors), and duty cycle. As mentioned previously, each counter/frequency divider circuit of frequency-divider circuitries 232 and 432 can be connected to several different output sources including global clock networks, local clock  
20 networks, and external clock buffers. By providing these flexible multiplexing regions on the divider circuit outputs, a user can advantageously configure their system in a very flexible manner. PLL circuitries 210 and 410 can thus be used to generate multiple internal clock references as well  
25 as provide off-chip reference clocks. Advantageously, a single frequency divider circuit can be used to generate both an internal reference clock and an external clock reference. Other advantages include being able to dynamically switch to any of the multiple input reference signals (in PLL  
30 circuitry 410) and to any of the global or local clocks. Allowing a user to dynamically configure PLL circuitry of the

invention avoids having to reprogram an entire PLD, which advantageously reduces overall system cost.

FIG. 7 shows an example of a clock multiplexer pattern that can be used with PLL circuitries of the invention. Pattern 700 includes two general purpose PLL circuitries 710, which may be, for example, either PLL circuitry 210 or 410. Each vertical line can be thought of as a single multiplexer with each circle representing a signal that can connect to the multiplexer. CLKPIN# represents standard clock pins, while nCLKPIN# represent additional clock pins available when the input clock is not a differential signal. The GCKDRV# (global clock driver) and LCKDRV# (local clock driver) signals provide a way for generic logic to drive onto clock networks without having to first drive out via an I/O pin and then back into the clock network via another I/O pin. These multiplexer connections can be used for signals that have a high fanout.

FIG. 8 shows an example of a multiplexer pattern for external clock outputs that can be used with PLL circuitries of the invention. Pattern 800 includes output pins 812 and general purpose PLL circuitry 810, which may be, for example, either PLL circuitry 210 or 410. Any output signal from PLL circuitry 810 can be routed to any output pin 812. The extclken# (external clock enable) signals advantageously allow a user to dynamically enable and disable clock pins synchronously. This can be used to implement a system power-down capability to reduce power consumption. Note that the even numbered outputs (i.e., ECK0, ECK2, ...) can be used with their adjacent odd numbered outputs (i.e., ECK1, ECK3, ...) for differential signaling.

FIG. 9 shows an alternative arrangement to multiplexer circuitries 228/428 and frequency-divider

circuitries 232/432. Cascaded PLL output stage 900 advantageously allows PLL circuitries of the invention to programmably divide down signal frequencies by orders of magnitude. The output of any of the first n-1 frequency dividers 932 (where n is the total number of frequency dividers) can be programmably selected by the appropriate multiplexer of multiplexer circuitry 928 to be the input of the next frequency divider 932. Thus, for example, the output of frequency divider C0 can be used as an on-chip local clock and as an input to frequency divider C1. Moreover, the programmable cascading does not need to begin with the output of frequency divider C0, nor does it need to continue to the nth frequency divider (which in this embodiment is divider C5). For example, the output of divider C2 can be cascaded to divider C3, whose output can be cascaded to divider C4, while the outputs of dividers C0, C1, and C5 can be used independently. Note that the VCO/test clk input to each frequency divider represents the multiple VCO output signals.

FIG. 10 shows an embodiment of configurable clock buffer circuitry in accordance with the invention. Advantageously, clock buffer circuitry 1000 supports generic I/O functionality as well as I/O clock functions and both input and output capability. Buffer circuitry 1000 includes multiplexers 1062 and 1064; buffer/drivers 1066, 1068, 1070, 1072, and 1074; and differential buffer 1076. Buffer circuitry 1000 is coupled to I/O-clock pins 1078 and can be configured to allow pins 1078 to be driven by PLL circuitry (thus making them clock pins) or to be driven by an I/O interface (thus making them generic I/O pins). Buffer circuitry 1000 can further be configured to allow one of pins 1078 to be used as a PLL external feedback pin (thus

becoming a delay compensation buffer). When buffer circuitry 1000 is configured bidirectionally (allowing both input and output), PLL circuitry can be configured as a zero delay buffer. This is preferable to known methods of using 5 delay cells because only the buffers being compensated out are used in this configuration.

Preferably, all clock sources (global clock, local clocks, and external clocks) associated with PLDs of the invention can be synchronously enabled and disabled. This 10 allows users to dynamically shut down and turn on various portions of their design for power management. FIG. 11 shows synchronous PLL enablement circuitry in accordance with the invention. Enablement circuitry 1100 includes latch 1182, AND gate 1184, and clock driver 1186. Signal ENOUT is a core 15 signal under user control used to dynamically control enabling and disabling of clocks. Signal ENOUTCTRL is a programming bit that allows the clock to always be enabled if a user does not use the disable feature. NPST is the register preset, which is active low, meaning that a low 20 voltage signal (e.g., a logical 0 signal) at that input causes the output to go high.

Note that while multiplexers have been shown throughout the FIGS., they may be alternatively replaced with other types of programmable logic connectors (PLCs). For 25 example, PLCs can be a relatively simple programmable connector such as a switch or a plurality of switches for connecting any one of several inputs to an output. Alternatively, each PLC can be a somewhat more complex element which is capable of performing logic (e.g., by 30 logically combining several of its inputs) as well as making a connection. In the latter case, for example, each PLC can be product term logic, implementing functions such as AND,

NAND, OR, or NOR. Examples of components suitable for implementing PLCs are EPROMs, EEPROMs, pass transistors, transmission gates, antifuses, laser fuses, metal optional links, etc.

5 Further note that PLDs having PLL circuitry of the invention are not limited to any one technology, but advantageously can be implemented in various technologies.

As mentioned above, PLCs (e.g., multiplexers) and divider circuits of the invention are programmable, and their 10 programmable parameters may be stored in various types of programmable, function control elements ("FCEs") (although with certain implementations (e.g., fuses and metal optional links) separate FCE devices are not required.) FCEs can be implemented in any of several different ways. For example, 15 FCEs can be SRAMs, DRAMs, first-in first-out ("FIFO") memories, EPROMs, EEPROMs, function control registers (e.g., as in Wahlstrom U.S. patent 3,473,160), ferro-electric memories, fuses, antifuses, or the like. The FCEs that control the PLCs and divider circuits of the invention are 20 preferably programmed in the same way and at the same time that programmable logic 108 in FIG. 1 is programmed.

Although the circuitry of the invention has many possible applications, one illustrative use is shown in FIG. 12. Data processing system 1200 includes programmable 25 logic device 100, which is an integrated circuit, and may be an integrated circuit chip, that includes PLL circuitry in accordance with the invention. PLD 100 may be field programmable, mask programmable, or programmable in any other way. It may be one-time-only programmable, or it may be 30 reprogrammable. System 1200 may also include one or more of the following components: a processor 1203; memory 1205; I/O circuitry 1207; and peripheral devices 1209. These

components are coupled together by a system bus 1211 and are populated on a circuit board 1213, which is contained in an end-user system 1215. Communication among the various components shown in FIG. 12, and/or with external circuitry, 5 may be of any known type to any desired extent.

System 1200 can be used in a wide variety of applications, such as computer networking, data networking, instrumentation, video processing, digital signal processing, or any other application where the advantage of using 10 programmable or reprogrammable logic is desirable. PLD 100 can be used to perform a variety of different logic functions. For example, PLD 100 can be configured as a processor or controller that works in cooperation with processor 1203. PLD 100 may also be used as an arbiter for 15 arbitrating access to a shared resource in system 1200. In yet another example, PLD 100 can be configured as an interface between processor 1203 and one of the other components in system 1200. Note that system 1200 is only exemplary and in no way should be construed to limit the true 20 scope and spirit of the invention.

Thus it is seen that highly configurable PLL circuitry outputting multiple signals having programmable phases and frequencies for programmable use as external or internal clocks is provided. One skilled in the art will 25 appreciate that the invention can be practiced by other than the described embodiments, which are presented for purposes of illustration and not of limitation, and the invention is limited only by the claims which follow.